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Review article

Type and number of environmental impact categories used in livestock life cycle assessment: A systematic review

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ABSTRACT

Life cycle assessment (LCA) is an important tool to evaluate environmental 'hot spots' in livestock systems and recommend production improvements. However, it is common for livestock LCA to investigate only a narrow subset of environmental impacts to simplify results for decision-makers, which makes it difficult to fully understand the tradeoffs among environmental impacts and identify the most relevant mitigation options. We completed a systematic review of the livestock LCA literature to better understand the impact categories included and the progress made towards more comprehensive LCA. Our search of publications between 2000 and 2016 identified 173 relevant peer-reviewed papers. Nearly all the publications (98%) included climate change as an impact category and almost one-third of the publications (28%) focused solely on that one category. Biodiversity, ionizing radiation, and particulate matter were the least common categories addressed. Cattle LCA, including dairy or beef, were the livestock species most frequently evaluated. Our analysis shows that while the number of multi-category livestock LCA (LCA with 4 or more impact categories) increased over time, LCA including 1–3 impact categories (which we define as "simplified LCA") increased at a higher rate than multi-category LCA. Simplified LCA therefore remain the most prevalent in the literature. Publications that included multiple impact categories were better able to identify environmental impact tradeoffs among livestock production systems and management scenarios. To compare results across livestock LCA studies, it is necessary to increase the standardization of system boundaries, functional units, impact frameworks and mandatory inputs. The optional steps of normalization and weighting in the life cycle impact assessment can also help decision-makers prioritize which environmental impacts to address. More work that includes a greater number of impact categories in livestock LCA is sorely needed to more fully understand and to harmonize the communication of the environmental performance of livestock production systems.

1. Introduction

The global demand for livestock products is expected to increase by 70% by 2050 (Opio et al., 2013), underscoring the importance of minimizing environmental impacts incurred during livestock production. These impacts are well documented: livestock production is a major contributor to greenhouse gas emissions (GHG) (Steinfeld et al., 2006), water consumption and pollution (Mekonnen and Hoekstra, 2012), land-use and land-use change (FAO, 2009), and loss of biodiversity (Herrero et al., 2009). However, livestock production systems are a critical source of protein and socio-economic income in much of the developing world (Randolph et al., 2007) and in developed regions (White and Hall, 2017). Additionally, under certain management practices, livestock may increase soil carbon sequestration potential (Reeder and Schuman, 2001; Rowntree et al., 2016), promote bird habitat (Derner et al., 2009), and improve grassland heterogeneity (Wrage et al., 2011).

Substantial efforts in the public and private sector are underway to increase the sustainability of livestock production. Policies aimed at improving environmental performance can be found in California – the United States' leading milk producer – which recently passed legislation to adopt regulations "to reduce methane emissions from livestock manure and dairy manure management operations by up to 40% below the dairy sector's and livestock's sector's 2013 levels by 2030 (SB-, 1383,

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2016; http://www.leginfo.ca.gov/). Australia and Canada have also taken steps to reduce livestock's climate impact through the Carbon Farming Initiative (C2011A00101, 2011) and Alberta's Greenhouse Gas Reduction Program (Alberta and Alberta, 2017), respectively. In Europe, the European Commission established the Product Environmental Footprint, which includes livestock products, as a method to communicate environmental performance throughout a product's life-cycle (European Commission, 2016a). Other initiatives include the Livestock Environmental Assessment and Performance (LEAP) partnership, a multistakeholder group focused on improving the environmental, economic, and social viability of livestock supply chains (FAO, 2017).

Policies and supply chain initiatives are increasingly based on whole-farm or life cycle assessment (LCA) in order to identify environmental 'hot spots' and improve production (UNEP/SETAC, 2012). Life cycle assessments quantify the potential environmental impact of a product from the raw materials' extraction to final disposal, including direct and indirect effects of production and consumption on issues like land and resource use. The practice of LCA is guided by standards published by the International Organization for Standardization (ISO, 2006a, 2006b) and includes four main steps: (1) goal and scope definition, (2) life cycle inventory analysis (LCI), (3) life cycle impact assessment (LCIA), and (4) interpretation of results. Optional steps in the LCIA include normalization and weighting, which can help decision-makers interpret LCA results and determine where to prioritize efforts aimed at reducing a product's environmental impact (Laurent and Hauschild, 2015). The final interpretation step summarizes and discusses the results of the LCI and LCIA (ISO, 2006a, 2006b).

Life cycle assessments are widely used across the livestock industry. De Vries and de Boer (2010) reviewed 21 LCA that examined the environmental impacts of pork (five studies), chicken (two studies), beef (three studies), milk (nine studies), and egg production (two studies) in different countries. More recent work investigating LCA of global beef production (de Vries et al., 2015) identified 16 different studies in North America (six studies), Europe (eight studies), and Oceania (two studies). The growing prevalence of livestock LCA in the peer-reviewed literature has led to greater acceptance of this methodology as a means of accounting for the full scope of environmental impacts from the livestock sector (Roy et al., 2009). The European Commission, for example, established the European Platform on Life Cycle Assessment, which recommends the use of LCA for measuring and communicating the life cycle environmental performance of a product (EU, 2015, 2016). Unlike other efforts, the guidance provided by the European Commission requires that at least three impact categories be included in the LCA (European Commission, 2016b).

The inclusion of livestock LCA studies in regulatory or other decision-making frameworks is based on the underlying assumption that the methodology captures the entirety of the product's environmental impact. However, it is common for livestock LCA to investigate only a narrow subset of environmental impacts in order to simplify results for decision-makers (Van Hoof et al., 2013). In their review of beef LCA, de Vries et al. (2015) found that all studies included the midpoint impact climate change in the LCA, but only half the studies or fewer examined land-use, energy use, eutrophication potential, and/or acidification potential. In LCA, a midpoint category describes a proximate impact along the environmental chain that can be measured before the endpoint impact is realized (e.g., GHG emissions are a midpoint indicator for average global temperature changes) (Jolliet et al., 2003).

In the absence of clear communication and justification for simplified LCA (e.g., carbon and water footprints or single attribute LCA), a narrow focus leads to the oversimplification of results and makes it difficult to determine the full scope of a product's environmental impacts. While simplified LCA, i.e., LCA with 3 or fewer impact categories, are valuable tools to conceptualize specific environmental impacts, they cannot accurately reveal the trade-offs that exist among different impacts and mitigation options, introducing the possibility of shifting environmental burden from one impact to another (Teillard et al., 2016).

The surge of simplified LCA publications in the livestock literature has led to calls within the scientific community for more comprehensive livestock LCA and greater transparency when interpreting study results (Roy et al., 2009; Teillard et al., 2016; Thoma et al., 2013a, 2013b). To date, most reviews of the livestock LCA literature focus on one livestock species (de Vries et al., 2015), recent methodological advances (Roy et al., 2009), or review and compare the results for a few environmental impacts (de Vries and de Boer, 2010; Garnett, 2009; Nijdam et al., 2012). We address this gap in the literature by completing the first systematic review of all livestock LCA to characterize the inclusion of environmental impacts. The objectives of our review were to: (1) quantitatively characterize the impact categories in the livestock LCA literature, (2) identify and review studies that examine 10 or more impact categories, and (3) evaluate the livestock LCA literature to benchmark the progress made towards more comprehensive analyses. We hypothesized that the attention given to this topic would have resulted in an increase in the numbers of impact categories in published LCA over time.

2. Methods

2.1. Literature search

We searched for articles using the terms "livestock" AND "LCA" or "livestock" AND "life cycle assessment" or "livestock" AND "life cycle analysis" in the 'topic' fields on the Web of Science and EBSCO database. In both databases, we searched for papers published between January 1, 2000 and December 31, 2016 (inclusive). Furthermore, we supplemented our results with papers included in a previous livestock LCA review that spanned 2000 – 2013 (Thoma, 2015). We also cross-checked references in papers we categorized as "reviews" and included the publications that were not captured if they met our inclusion criteria (see below).

2.2. Screening process

Our systematic review process closely followed Gurwick et al. (2013) and the guidelines in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Statement (Moher et al., 2009). We excluded search results that were published in languages other than English and results where only an abstract was included. The remaining results were placed into one of two categories. The first category included papers that appeared in peer-reviewed publications and reported original data or results from observations, experiments, or models. These papers were LCA or partial LCA with minimum system boundaries from cradle-to-farm-gate with a livestock product (e.g. "1 kg of energy-corrected milk" or "1 kg of beef") as the functional unit. We excluded papers based on a footprint analysis (i.e., carbon footprint, water footprint, energy footprint) unless the study methodology explicitly mentioned undertaking an LCA, rather than a footprint, approach. Footprint analyses, by their very nature, focus on only one impact category, and excluding them in our inclusion criteria reduced the potential for introducing bias into our results.

The second category included all the publications that did not meet our inclusion requirements. We did not include in this analysis other publication types like news stories, book chapters, or editorial notes. Additional results excluded were papers that did not include a livestock LCA despite being identified in our search, papers that evaluated or described an improved method for analyzing the life cycle of livestock but did not contain an LCA, or papers that did not meet the system boundary requirements listed above, e.g. conducted an LCA for livestock feed or manure handling for energy production.

2.3. Literature characterization

We conducted a categorization process for the papers identified in our initial screening. Our first objective was to quantitatively characterize recent publications (2000–2016) by determining both the type and number of impact categories examined in the livestock LCA literature. Based on Jolliet et al. (2004), we categorized impacts within publications into the following twelve midpoint impact categories:

- Acidification
- Biodiversity
- Climate change (or global warming potential)
- Ecotoxicity
- Eutrophication
- Human toxicity
- Ionizing radiation
- Land use or land occupation
- Ozone depletion
- Particulate matter
- Photochemical ozone formation or photo-oxidant formation
- Resource depletion (including biotic and abiotic resources; e.g., fossil fuel, electricity, water, etc.)

We excluded two midpoint impact categories – causalities and noise – as not relevant to this review. We referred to the category of 'species and organism dispersal' simply as 'biodiversity.'

2.4. Reviewing multiple impact category studies

Our second objective was to closely review studies that contained ten or more impact categories in their LCIAs. We sought to better understand the livestock species and products examined in these studies, whether and how the impacts were prioritized, and if any of the studies conducted normalization and weighting of the midpoint impact results. Midpoint categories refer to effects midway along a cause and effect chain connecting emission to the environment and impacts to areas of protection which are also known as endpoint categories. The list presented above are all midpoint categories, while human health, ecosystem health and natural resources – each of which combine the effects of several midpoint impact categories – are considered endpoint categories (Bare et al., 2000). Endpoint impact categories, if applicable, were also documented.

2.5. Evaluating the livestock LCA literature over time

For our third objective we recorded the number of studies on livestock LCA and the number of impact categories included in each study for each year during the search period. The studies were grouped as follows: one to three impact categories, four to six impact categories, seven to nine impact categories, and ten to twelve impact categories. We also sorted studies by the type of livestock species or products.

2.6. Statistical analysis

To evaluate the progress made towards more comprehensive LCA during the search period, we pooled the data into three-year averages to smooth the variation in our results. We calculated the 95% confidence interval for each of the four impact category groupings 1–3, 4–6, 7–9, and 10–12) to determine if there were significant differences in the mean number of publications published over time.

3. Results

Nine hundred and thirty-five unique publications included our search terms. However, only 20% of these papers were relevant for this analysis. We excluded 762 publications, 633 (80%) of which were not considered primary research, unrelated to our review, or the titles and/or abstracts incidentally mentioned the terms "life cycle," "assessment," or "LCA." We further excluded 19 literature reviews of livestock LCA and another 21 publications that we classified as methodological. One publication (Büsser and Jungbluth, 2009) did not meet the system boundary requirement (i.e., a minimum of cradle-to-farm-gate) and another included none of our 12 impact categories (Powell et al., 2013). An additional 48 publications focused on a functional unit outside the scope of this review [e.g., annual food production (Styles et al., 2015), ton of feed (Tongpool et al., 2012), and ton of feedlot dry manure (Wu et al., 2013)]. We removed 21 publications from further review because they explicitly focused on footprint analyses (i.e., carbon, water, nitrogen, and energy). The remaining 18 publications were primary research using LCA, but they did not include assessment of livestock.

After excluding non-pertinent references as described above, our livestock LCA dataset included 173 publications (Table S1). The 137 papers identified through database searches were supplemented with an additional 36 publications: 24 publications from (Thoma, 2015) and 12 from other LCA review papers captured by our search (de Vries and de Boer, 2010; de Vries et al., 2015; Gerber et al., 2014; McAuliffe et al., 2016; Röös et al., 2013; Winkler and Winiwarter, 2015).

The most frequently included impact category in these references was climate change, represented in 98% of the papers (Fig. 1). This category, except for two papers, was also the topic of the 96% of publications that only evaluated one impact category (Table 1). The second most frequently reviewed category, resource depletion, was included in 54% of the studies. The least frequently reviewed factors were particulate matter, ionizing radiation, and biodiversity. Only a small number of studies (8%) examined more than six impact categories (Table 1).

The reported impact categories were also dependent on the livestock species examined (Fig. 2). Cattle, either dairy or beef, received the most attention in the livestock LCA literature; these LCA generally included only one to three impact categories (60% of cattle LCA publications). Sheep and multiple species LCA (i.e., LCA that included two or more livestock species or products) followed a similar pattern: 88% of sheep publications and 78% of multiple species publications contained one to three impact categories. Pork and poultry LCA generally included a greater number of four or more impact categories, 61% and 86% of publications, respectively.

We also examined the trend in LCA publications from 2000 to 2016 (Fig. 3). The total number of publications exhibited quadratic growth during the time period (r^2 = 0.99). The first LCA including ten or more categories was in 2012 (Nguyen et al., 2012; Fig. 4 and Table 2). However, since 2010, the average number of simplified LCA increased at a higher rate than any other category, and most of this growth was

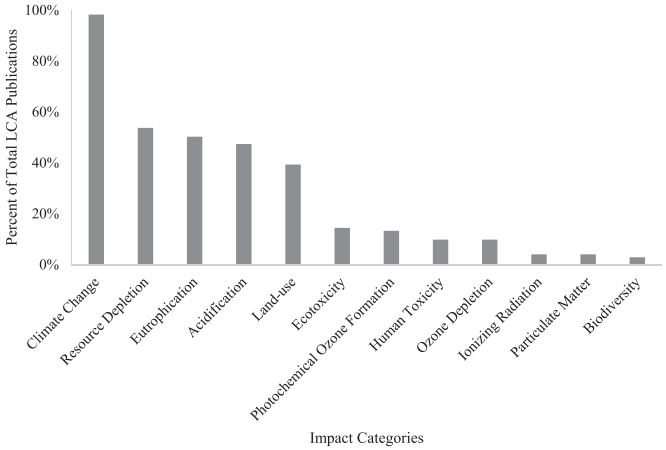

Fig. 1. Percent of life cycle assessment (LCA) publications of total number of publications including each specific impact category (2000–2016; n = 173).

Table 1
Frequency of occurrence of each impact category across all studies.

Impact Category	Number of Impact Categories Included												
	1	2	3	4	5	6	7	8	9	10	11	12	Total Publications
	% of Total Publications												
Climate Change	27	12	16	13	15	8	0	2	3	1	1	1	98
Resource Depletion	1	5	9	10	14	7	0	2	3	1	1	1	54
Eutrophication	0	0	9	12	15	8	0	2	3	1	1	1	50
Acidification	0	0	7	12	15	6	0	2	3	1	1	1	47
Land-use	0	8	8	4	10	3	0	1	3	1	1	1	39
Ecotoxicity	0	0	0	2	1	5	0	1	3	1	1	1	14
Photochemical Ozone Formation	0	0	0	0	3	4	0	2	2	1	1	1	13
Human Toxicity	0	1	0	0	0	2	0	2	3	1	1	1	10
Ozone Depletion	0	0	0	0	1	2	0	1	3	1	1	1	10
Ionizing Radiation	0	0	0	0	0	0	0	0	2	1	1	1	4
Particulate Matter	0	0	0	0	0	1	0	0	1	1	1	1	4
Biodiversity	0	0	0	1	0	1	0	0	1	0	0	1	3
Total Publications	28	12	16	13	15	8	0	2	3	1	1	1	

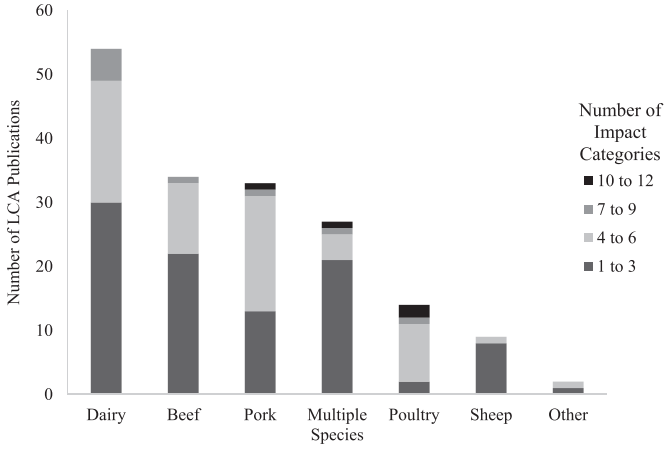

Fig. 2. The number of impact categories examined in LCA studies by livestock species. Multiple species refer to LCA that included two or more livestock species or products (e.g., milk and eggs) in their analysis. Other refers to LCA that investigated goat or buffalo production.

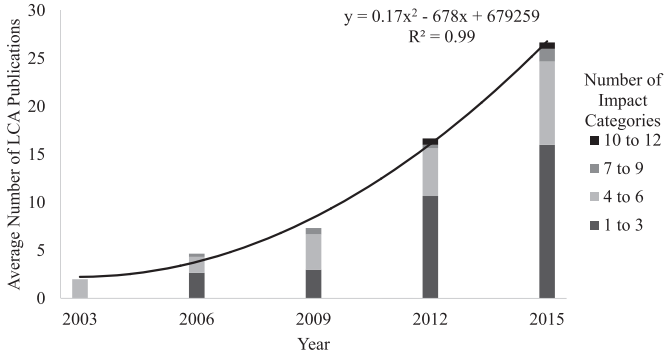

Fig. 3. The number of LCA publications and impact categories examined by each study from 2000 to 2016 using three-year averages.

driven by single impact category LCA. In comparison, the numbers of publications including four or more impact categories increased only slowly over time (Fig. 4).

Over the 16 years of this review, only four publications examined 10–12 impact categories (Table 2). One publication analyzed multiple livestock products (Head et al., 2014), while the other three focused on a single species: poultry (Bengtsson and Seddon, 2013; Paolotti et al., 2016) and pork (Nguyen et al., 2012). Bengtsson and Seddon (2013) reported on production in Australia; the remaining three publications

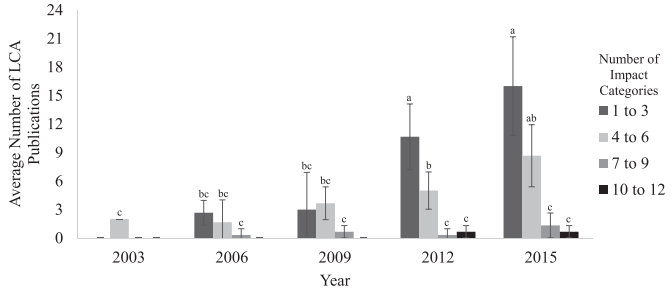

Fig. 4. Three-year averages of the number of LCA publications and impact categories examined by each study from 2002 to 2016. Error bars represent the 95% confidence interval, the lower bound corresponds to 2.5th percentile and the upper bound corresponds to 97.5th percentile. Means with different letters were significantly different ($P < 0.05$).

examined livestock production systems in Europe. Two studies (Nguyen et al., 2012; Paolotti et al., 2016) restricted their system boundary to cradle-to-farm-gate, and the other two (Bengtsson and Seddon, 2013; Head et al., 2014) examined impacts up to the point of retail in the supply chain. Head et al. (2014) included all twelve impact categories. Two studies (Nguyen et al., 2012; Paolotti et al., 2016) excluded biodiversity; Bengtsson and Seddon (2013) excluded biodiversity and particulate matter. Land-use was a priority category and discussed at length in three of these publications (Head et al., 2014; Nguyen et al., 2012; Paolotti et al., 2016). Each study performed the optional normalization and weighting steps, but they all used different LCIA frameworks.

4. Discussion

We are confident that our search methodology captured the breadth of the livestock LCA literature, but our review likely missed some relevant publications despite the use of multiple databases, search terms, and publications from previous literature reviews. The most recent literature review captured by our search (McAuliffe et al., 2016) included 36 publications in their review of pork production LCA. Our database search overlapped with 15 of the publications in their review. However, we excluded eight of these publications from our final analysis because they did not meet our functional unit requirements. Of the 21 publications not captured by our search, we ultimately included five publications as the other sixteen did not meet our inclusion criteria. This result was similar for the other literature reviews we used for publications to supplement our review. At most, two publications in each of these reviews (n = 19) were not identified by our search.

Table 2
Livestock LCA that included 10–12 midpoint impact categories.

Study	Livestock species	Location	System boundary	Functional unit	Midpoint Impact Categories[a]	Normalization & Weighting	Endpoint Impact Categories
Bengtsson and Seddon (2013)	Poultry	Australia	Cradle-to-retailer	1 t of roast chicken and breast fillet	**Climate change**; Ozone depletion; Human toxicity; Ionizing radiation; Photochemical ozone formation; Acidification; Eutrophication; Ecotoxicity; Land-use; **Resource depletion**	Bengtsson and Howard (2010)	n/a
Head et al. (2014)	Beef and veal; Pork; Poultry; Lamb; Rabbit and hare; Dairy products; Eggs	Denmark	Cradle-to-retail	1 kg of product at point of retail in supermarket (e.g. 1 kg of edible cuts of meat; 1 kg fat corrected milk)	Climate change; Ozone depletion; Human toxicity; Particulate matter; Ionizing radiation; Photochemical ozone formation; Acidification; Eutrophication; Ecotoxicity; **Land-use**; Resource depletion; Biodiversity	ReCiPe method	Climate change (kg CO_2-eq); Human health (DALY); Nature and environment (species yr.)
Nguyen et al. (2012)	Pork	European Union	Cradle-to-farm-gate	1 kg pig meat carcass weight (delivered from farms)	Climate change; Ozone depletion; Human toxicity; Particulate matter; Ionizing radiation; Photochemical ozone formation; Acidification, Eutrophication, Ecotoxicity; **Land-use**; Resource depletion	Stepwise 2006	Ecosystems; Human well-being; Resource productivity
Paolotti et al. (2016)	Poultry	Italy	Cradle-to-farm-gate	1 t of meat	Climate change; Ozone depletion; Human toxicity; Particulate matter; Ionizing radiation; Acidification; Eutrophication; Ecotoxicity; **Land-use;** Resource depletion	Eco-Indicator 99	Ecosystem quality; Human health; Resource consumption

[a] Bold text indicates the impact category that was the focus in the life cycle impact assessment (LCIA).

4.1. Multiple impact categories highlight trade-offs

While this review generally supports our hypothesis that livestock LCA include a greater number of impact categories over time (Fig. 3), there are still relatively few publications with LCA of 7 or more impacts. Our review is the first to quantitatively show that livestock LCA overwhelmingly focus on GHG emissions and climate change. It expands on the findings of de Vries et al. (2015) who found that climate change is well-studied in livestock LCA, but other impact categories are seriously lacking. Climate change impact is a critical element of livestock production systems; however, focus on this impact category is insufficient for defining the full LCA.

The impact category of biodiversity illustrates the importance of this point. Our review identified only five studies (3%) that included biodiversity. Publications focused on climate change or a narrower set of impact categories (e.g., resource depletion, eutrophication, acidification, and land-use) often recommend management practices or policies that encourage system intensification to drive down GHG emissions (Capper, 2011; Gerber et al., 2010; Hagemann et al., 2011; O'Brien et al., 2016; Stackhouse et al., 2012).

These recommendations can jeopardize biodiversity directly by discouraging production on traditional grazing lands and increasing reliance on grain and forage crops. The removal of livestock grazing from ecosystems with long histories as semi-natural grasslands, such that the ecosystem converts to another vegetative state, may alter species composition (Cingolani et al., 2014) and habitat for key species or species of concern (Derner et al., 2009). Policies that promote feeding livestock oils and grains as a way to increase animal production and decrease emission intensity, such as Australia's Carbon Farming Initiative and Alberta's Greenhouse Gas Reduction Program (Cooper et al., 2013), may endanger biodiversity because of intensive cropping practices that, in addition to changing land-use, can lead to competition for limited water resources and harmful nutrient runoff (Tilman et al., 2002).

Two (Picasso et al., 2014; Tendall and Gaillard, 2015) of the five studies (Head et al., 2014; Kim et al., 2013; Müller-Lindenlauf et al., 2010) that included biodiversity demonstrated the importance of including multiple impacts. In their study of different beef grazing systems in Uruguay, Picasso et al. (2014) found that reducing climate change impacts were associated with increasing negative impact on native grassland biodiversity because of direct reduction of habitat. They conclude that LCA should incorporate multiple impact categories because of the significant potential for tradeoffs that exist between climate change and other environmental impacts. In addition, Tendall and Gaillard (2015) determined that without inclusion of multiple impact categories in their methodology that their analysis would not have identified an important tradeoff between the impacts of water use on aquatic biodiversity and system productivity. While they did not find significant tradeoffs for biodiversity, the other three studies (Head et al., 2014; Kim et al., 2013; Müller-Lindenlauf et al., 2010) also advocated for more comprehensive LCA in order to identify tradeoffs among crucial, but understudied environmental impact categories.

4.2. Interpretation of LCA results

4.2.1. Standardization

The few existing multi-category livestock LCA suggest improvements that should enhance the ability of decision-makers to improve the environmental sustainability of livestock production. As has been noted in earlier reviews (de Vries and de Boer, 2010; FAO, 2016), the four studies in Table 2 have varying functional units, system boundaries, and narrow geographical areas. The system boundary and functional unit in each LCA ranged from cradle-to-farm-gate to cradle-to-retail and 1 t of meat to 1 kg of product at point of retail in supermarket, respectively. In their review of whole farm system models of beef and dairy production systems, Crosson et al. (2011) found similar

patterns of variation in system boundary and functional units limiting direct comparisons of studies.

More broadly, these patterns were apparent in the rest of the publications we analyzed. Furthermore, many studies are focused on Europe, Australia and North America (de Vries and de Boer, 2010; de Vries et al., 2015; Nijdam et al., 2012), with fewer primary studies and reviews addressing Africa, Asia, and South America. We agree with the results from the review of Nijdam et al. (2012) that while the variability in LCA reflects different livestock production systems (e.g., production in tropical versus temperate climates, and intensive versus extensive management), the lack of standardization coupled with the limited inclusion of multiple impact categories makes it challenging to compare livestock alternate production systems and implement choices related to production improvement.

4.2.2. Normalization and weighting

The normalization and weighting steps were critical to interpreting the multi-category studies we reviewed (Table 2). Although not required steps in LCIA, normalization and weighting of LCIA results ease their interpretation. Normalization is a method of determining the magnitude of an impact category relative to a 'normal' value or reference (ISO, 2006b). The reference value is usually based on global or regional normalization factors or sometimes on a per capita basis (Laurent and Hauschild, 2015). Weighting is the final part of the LCIA, and it involves multiplying the normalized results of each impact category with a weighting factor, which reflects the relative importance of the impact category. The weighted results have the same unit and, thus, can be summed to create a single score of environmental impact for a given product or scenario. These steps can help decision-makers determine where to prioritize and focus efforts aimed at reducing a product's environmental impact. However, weighting, in particular, is subjective in that it is based on the values and interests of the researchers, practitioners, and other stakeholders involved in the study (Finnveden et al., 2009) and also obscures trade-offs among the contributing categories.

Endpoint impact categories can also help with interpreting the results of an LCIA. Midpoint impacts are reported in several different units and it can be challenging to compare results because of this variation. The endpoint method combines the multiple midpoint indicators into three standardized endpoints which are scientifically-based: human health, ecosystem quality, and resource depletion (Goedkoop et al., 2009). A value judgment, thus, only needs to be applied to these three categories when combining them into a single score. While three of the four multi-category studies we reviewed calculated endpoint impact categories, the endpoints selected were not comparable across all studies. Paolotti et al. (2016) and Nguyen et al. (2012) both calculated scores for ecosystem quality, human health, and resource consumption/productivity. Head et al. (2014) did not include a resource component, but rather an endpoint category for climate change. Given these results, we concur with Roy et al. (2009) that greater effort towards consensus is needed if endpoint impact categories are to be used effectively as a means to help decision-makers interpret results across different studies.

5. Conclusion

Despite decades of LCA development and repeated calls for multi-category livestock LCA, most studies still focus on a single impact category. Simplified LCA are important tools for highlighting the magnitude of one or a select set of environmental impacts. But, because they ignore other potential impacts they risk misinterpreting and misrepresenting the full extent of livestock production impacts on the environment – including potential benefits, as identified in some studies. We recommend that the convention in the livestock LCA literature shift to include multiple environmental impact categories that are normalized and combined consistently into standardized endpoint impact categories to support management and regulatory decisions.

The current, and vital, emphasis on climate change does not preclude the opportunity to address other environmental effects of livestock. Researchers and funders should move quickly to provide decision-makers with the information they need to sustainably intensify livestock production without seriously jeopardizing other aspects of the environment. Environmental tradeoffs will always occur in livestock production, but the nature and severity of these tradeoffs can be better understood, and therefore managed, through assessments that evaluate multiple impacts in parallel.

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Conflicts of interest

None.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.livsci.2018.01.008.

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